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Letter to the Editor

Constraints on mass ejection in black hole formation derived from black hole X-ray binaries

G. Nelemans, T. M. Tauris and E.P.J. van den Heuvel

Astronomical Institute, "Anton Pannekoek", University of Amsterdam, Kruislaan 403, NL-1098 SJ Amsterdam, The Netherlands

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Abstract. Both the recently observed high runaway velocities of Cyg X-1 ($\sim$ 50 km s^{-1}) and X-ray Nova Sco 1994 ($\geq$ 100 km s^{-1}) and the relatively low radial velocities of the black hole X-ray binaries with low mass donor stars, can be explained by symmetric mass ejection in the supernovae (SNe) which formed the black holes in these systems.

Assuming symmetric mass ejection in black hole formation, we estimate the amount of mass that must have been ejected in the stellar core collapse in order to explain the velocities of the above X-ray binaries. We find that at least 2.6 $M_\odot$ and 4.1 $M_\odot$ must have been ejected in the formation of Cyg X-1 and Nova Sco, respectively. A similar mass loss fraction ($f = 0.35$) for the black hole binaries with low mass donors, gives low velocities, in agreement with the observations.

We conclude that the black holes in X-ray binaries are all consistent with being formed in a successful SN in which mass is ejected. A possible kick at the formation of the black hole is not needed to explain their space velocities.

Key words: stars: black hole – supernova: mass-loss – binaries: evolution

The light curve and spectrum of the abnormally luminous type Ic SN 1998bw (Galama et al. (1998)) suggest that in this event a black hole was formed (Iwamoto et al. (1998)). The observations imply that a considerable fraction of the mass of the progenitor (a massive C/O core) was ejected in the explosion (Iwamoto et al. (1998)). Similarly, the observed overabundance of the elements O, Mg, Si and S in the atmosphere of the companion of Nova Sco 1994, indicates considerable mass ejection in the formation of this black hole (Israelian et al., 1999).

From a study of the z-distribution of the population of black hole X-ray binaries with low mass donors, White & van Paradijs (1996) conclude that the velocity dispersion of these X-ray binaries is of the order of 40 km s^{-1}. Since the velocity dispersion of the progenitor systems is expected to be around 17 km s^{-1}, they estimate the extra velocity that is given to the system in the formation of the black hole to be 20 – 40 km s^{-1}. This requires substantial mass ejection in the formation of a black hole if no asymmetric kicks are involved.

Recent determinations of the space velocity of Cyg X-1 (Kaper et al., 1999) and the radial velocity of Nova Sco (Bailyn et al., 1995) demonstrate that these black hole binaries have significantly higher runaway velocities than the black hole X-ray binaries with low mass donors.

In Table 1 we have listed the relevant properties of the galactic black hole binaries for which one, or more, of its velocity components have been measured.

Table 1. Properties of black hole X-ray binaries. The velocity of Cyg X-1 is its space velocity, all other velocities are radial velocities, so are lower limits

Source	M(M$_\odot$)	m(M$_\odot$)	P (d)	v (km s^{-1})
Nova Sco 1994	6.29-7.60	1.6 - 3.1	2.62	106±19
Cyg X-1	3.9-15.2	11.7-19.2	5.6	49±14
V 404 Cyg	6-12.5	0.6	6.5	8.5±2.2
A 0620-00	3.3-4.24	0.15-0.38	0.32	15±5
Nova Muscae	>4.45±0.46	0.7	0.43	26±5
Nova Oph 1977	5-7	0.7	-	38±20
GRO J0422+32	3.25-3.9	0.39	0.21	11±8
GS2000+25	6.04-13.9	0.26-0.59	0.35	18.9±4.2

Masses and periods from Ergma & van den Heuvel (1998) and references therein, velocities from Brandt et al. (1995) and references therein, except for GRO J0422+32 (Harlaftis et al., 1999) and GS2000+25 (Harlaftis et al., 1996) which are heliocentric γ-velocities. For Nova Sco 1994 we changed the velocity according to the new γ-velocity of 142 km s^{-1} (Shahbaz et al., 1999). Space velocity for Cyg X-1 is from Kaper et al. (1999).

Send offprint requests to: gijsn@astro.uva.nl

1. Origin of the black hole binary runaway velocities

There are two effects to accelerate a binary system by a supernova explosion. The first is caused by the ejection of material from the binary (Blaauw 1961). The centre of mass of the ejected matter will continue to move with the orbital velocity of the black hole progenitor. To conserve momentum, the binary will move in the opposite direction. The second one is an additional velocity kick, which is produced by asymmetries in the supernova explosion itself and for which there is strong evidence in the case of the formation of a neutron star (e.g. Lyne & Lorimer (1994), Hartman (1997)).

The current status quo of supernova simulations is that in order to get a successful supernova, in which the shock is reversed and matter is ejected, one needs to form a neutron star (Bethe and Wilson, 1985). If the supernova is not so energetic, there may be considerable fall back, turning the neutron star into a black hole (e.g. Colgate (1971); Woosley & Weaver (1995)). Formation of a black hole without an intermediate neutron star would then not result in mass ejection. However, if other mechanisms than neutrino heating will be found to reverse the supernova shock (e.g rotation), this conjecture of both mechanisms may be broken.

Brandt et al. (1995) have listed a number of scenarios for reproducing the high radial velocity measured in Nova Sco. They show that though mass ejection alone can explain the velocity of Nova Sco 1994, the allowed range of initial masses is very small. They therefore conclude that Nova Sco is formed in a delayed black hole formation, in which the kick, which is imparted to the initial neutron star, is responsible for a considerable fraction of the present system velocity. The black holes in the other binaries would then be formed by a direct collapse without mass ejection and kicks. The velocity dispersion found by White & van Paradijs (1996) can be explained by scattering at molecular clouds and density waves, since these binaries could be an old population (Podsiadlowski, private communication; see also Brandt et al. (1995)).

With the new discovery of the relatively high velocity of Cyg X-1, we think the above is unlikely, because now the two systems with highest mass companions must have formed through a delayed black hole formation, while the systems with low mass companions form in a direct collapse. This would mean that the success of the SN in which the black hole is formed is related to the nature of its binary companion, for which we see no reason

Tutukov & Cherepahshchuk (1997) discuss the system velocities of the X-ray binaries containing black holes and conclude that all velocities can be explained with mass ejection alone. However, they only consider the maximum velocity that can be obtained with the observed limits on the masses of both stars, assuming the shortest possible period at the moment of the SN and the maximum amount of mass that can be ejected without disrupting the binary. In that case, the pre-SN mass ratio is not independent of the final (observed) mass ratio and it would be better to use the current (observed) mass ratio, with which their equation (7) would become

$$v_{\max} = 192 \left(\frac{q_{\rm obs}}{1+q_{\rm obs}}\right)^{0.72} \qquad \mathrm{km\ s^{-1}} \tag{1}$$

See also the discussion in section 4.

We now investigate the effect of the mass ejection in more detail, assuming possible kicks are (relatively) unimportant.

2. Runaway velocities from symmetric SNe

Consider a circular pre-SN orbit consisting of a helium star with mass $M_{\rm He}$ (the progenitor of the black hole) and a companion star with mass m. Assume that the helium star explodes in a symmetric SN during which an amount of mass, ΔM is ejected instantaneously and decouples gravitationally from the system. If $\Delta M = M_{\rm He} - M_{\rm BH} < 0.5\,(M_{\rm He} + m)$ the binary will remain bound. The post-SN eccentricity, period and orbital separation are given by Bhattacharya & van den Heuvel (1991)

$$e_{\rm postSN} = \frac{\Delta M}{M_{\rm BH}+m} = \frac{1-\mu}{\mu} \tag{2}$$

$$P_{\rm postSN} = P_{\rm i}\,\frac{\mu}{(2\mu-1)^{3/2}} \tag{3}$$

where we define

$$\mu = \frac{M_{\rm BH}+m}{M_{\rm He}+m} = \frac{M_{\rm He}+m-\Delta M}{M_{\rm He}+m} \tag{4}$$

and subscripts i denote the pre-SN system. Since the observed black hole binaries all have short orbital periods ($<$ 7 days) tidal forces act to re-circularize the post-SN orbit. The parameters of the re-circularized orbit are given by

$$P_{\rm re-circ} = P_{\rm postSN}(1-e^2_{\rm postSN})^{3/2} = P_{\rm i}/\mu^2 \tag{5}$$

And similarly $a_{\rm re-circ} = a_{\rm i}/\mu$. Here we have ignored the effects of the impact of the ejected shell on the companion star and assume there is no mass loss or transfer during the re-circularization phase. From conservation of momentum one finds an expression for the resulting runaway velocity (recoil) of the system

$$v_{\rm sys} = \frac{\Delta M\, v_{\rm He}}{M_{\rm BH}+m} \tag{6}$$

where $v_{\rm He}$ is the pre-SN orbital velocity of the exploding helium star in a centre-of-mass reference frame. Together with Keplers third law we find

$$v_{\rm sys} = (G\,2\pi)^{1/3}\,\Delta M\, m\, P_{\rm re-circ}^{-1/3}\,(M_{\rm BH}+m)^{-5/3} \tag{7}$$

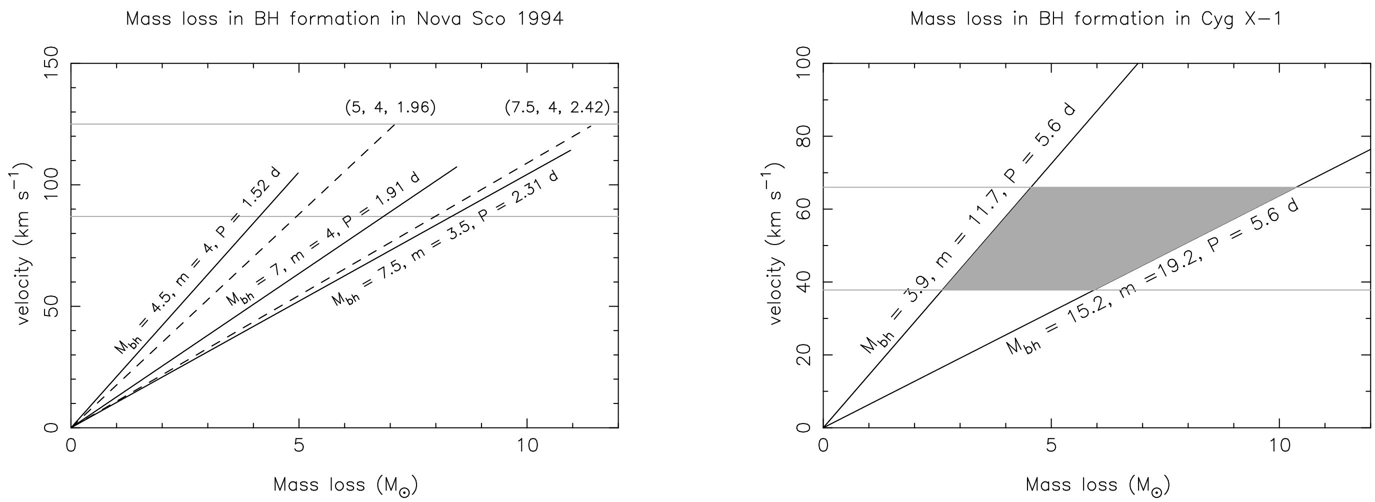

Fig. 1. Limits on the amount of mass ejected in the SN explosion that is required to explain the measured velocities. Left: Nova Sco 1994 with three possibilities of the binary parameters at the onset of the X-ray phase (solid lines; see text) and the two possibilities in the case 0.5 $M_\odot$ has been lost draining angular momentum (dashed lines). Right: Cygnus X-1 with two different solutions for the companion mass.

For convenience this equation can be expressed as

$$v_{\rm sys} = 213\left(\frac{\Delta M}{M_\odot}\right)\left(\frac{m}{M_\odot}\right)\left(\frac{P_{\rm re-circ}}{\rm day}\right)^{-\frac{1}{3}}\left(\frac{M_{\rm BH}+m}{M_\odot}\right)^{-\frac{5}{3}}\text{km s}^{-1}$$

If we know the masses of the stellar components and the orbital period after the re-circularization $(M_{\rm BH}, m, P_{\rm re-circ})$ we can calculate ΔM from the observed runaway velocity, $v_{\rm sys}$. However, we observe mass-transferring binaries which might have evolved due to loss of angular momentum by gravitational radiation or magnetic braking before the mass transfer started and/or might have transferred already a significant amount of mass from the donor to the black hole. Before applying equation (7) to the observed systems we have to correct for these effects.

Also, one has to check whether the binary before the SN would be detached, i.e. that both stars do not fill their Roche lobes at the moment the SN explodes.

3. Results

3.1. Nova Sco 1994

Shahbaz et al., (1999) have recently determined the present stellar masses in Nova Sco 1994 (GRO J1655-40). They find $M_{\rm BH} = 5.5-7.9\,M_\odot$ and $m = 1.7-3.3\,M_\odot$. The mass transfer in Nova Sco 1994 may already have been going on for a long period of time. From the luminosity and effective temperature of the donor star in this system one finds, using stellar evolution tracks, that the donor can not have started out with a mass larger than $4.0\,M_\odot$ at the onset of the X-ray phase (van der Hooft et al., 1998). As an example of combinations of present masses we use $(M_{\rm BH}, m)$ = (6, 2.5) and (7.75, 3.25). Assuming conservative mass transfer ($P_{\rm re-circ}/P_{\rm obs} = [(M_{\rm BH,obs}m_{\rm obs})/(M_{\rm BH}m)]^3$) some possibilities for the system configuration at the onset of mass transfer are the following combinations of $(M_{\rm BH}, m, P_{\rm re-circ})$: (4.5, 4.0, 1.52), (7.0, 4.0, 1.91) and (7.5, 3.5, 2.31). With these values and Eq. (7) we find that the present runaway velocity of 106 km s^{-1} is obtained for $\Delta M = 5.0\,, 8.4$ and $10.2 M_\odot$ respectively. This is shown in the left panel of Fig. 1 (solid lines). Note that all these lines are terminated at the amount of mass ejection that would result in a pre-SN orbit in which the companion would fill its Roche lobe. The minimum amount of mass that must be lost is 4.1 $M_\odot$ in the case of a black hole of 4.5 $M_\odot$, given $v_{\rm sys} > 87$ km s^{-1}.

If we relax the assumption of conservative mass transfer (as is suggested by the observation of jets from Nova Sco), and assuming the lost material drags along three times the specific angular momentum (Pols & Marinus (1994)), we calculated the orbits for the first two cases, assuming 0.5 $M_\odot$ was lost from the system. The resulting system parameters at the onset of the mass transfer then become (5, 4, 1.96) and (7.5, 4, 2.42) for the first two examples. These curves are plotted as dashed lines in Fig. 1. In this case at least 5 and 8 $M_\odot$ are lost, respectively.

3.2. Cygnus X-1

For Cygnus X-1 the presently best estimate of the masses of the stellar components is $M_{\rm BH} = 10.1\,M_\odot$ and $m = 17.8\,M_\odot$. Extremes of the allowed masses are given by $(M_{\rm BH}, m)$ = (3.9, 11.7) and (15.2, 19.2) respectively (Herrero et al., 1995). We assume no orbital evolution since the beginning of the mass transfer phase, because Roche lobe overflow can not have started long ago since the expected mass transfer rates then would be much higher. We use the values of the masses as given above and the present

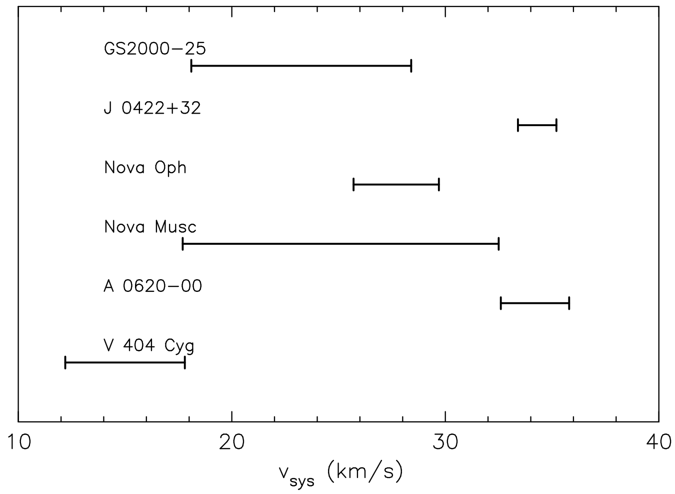

Fig. 2. Our estimated 3-D recoil velocity for the black hole X-ray binaries with low mass donors, for a supernova mass loss fraction $f \equiv \Delta M/M_{\rm He} = 0.35$. The limits represent the uncertainty in the black hole mass as given in Table 1

day orbital period of 5.6 days. We also neglect the small eccentricity that the orbit still has. The right hand panel in Fig. 1 shows the resulting allowed range of mass ejected in the formation of the black hole. For a present black hole mass of 3.9 $M_\odot$ at least 2.6 $M_\odot$ must have been ejected to produce the observed space velocity. For a black hole of 15.2 $M_\odot$ at least 6 $M_\odot$ must have been ejected.

3.3. The remaining black hole X-ray transients

Table 1 shows that all the black hole X-ray binaries with low mass donors have low velocities. As derived by White & van Paradijs (1996), the expected additional velocity component of these X-ray binaries is of the order of 20 – 40 km s^{-1}. In Cyg X-1 and Nova Sco at least 28 and 48% of the mass of the progenitor must have been ejected in the SN. Therefore we computed the velocities for these systems assuming a constant fraction of 35% of the helium star mass to be ejected and show the obtained range in velocities given the range in black hole masses in Fig. 2. The last five systems are all expected to have evolved during mass transfer to smaller periods, and all seem to be compatible with an initial systems close to (m, P) = (1 $M_\odot$, 0.74 d), cf. Ergma & Fedorova (1998). The systems shrink due to magnetic braking, so we assume $P_{\rm re-circ}$ = 1 d (see e.g. Kalogera (1999)). For V 404 Cyg we assumed an re-circularized period of 4 days and an donor mass of 1 $M_\odot$.

4. Discussion and conclusions

In this Letter we show that both the high observed velocities of Cyg X-1 and Nova Sco, and the low velocities of the black hole X-ray binaries with low mass donors can be explained by ejection of $\gtrsim$30% of the mass of the exploding helium star in the SN that formed the black hole. This removes the need to invoke a large kick for Nova Sco (and Cyg X-1) and at the same time a small or no kick for the remaining systems (Brandt et al., 1995), which seems highly unlikely to us.

The radial velocity of Nova Sco can only be explained by large mass-loss fractions ($\gtrsim$ 50%) and the assumption that the mass transfer has already started some time ago. If this mass transfer was non-conservative (consistent with observed jets), the velocity can be explained more easily. This may also be needed if Nova Sco also has a transverse velocity component.

Tutukov & Cherepahschuk (1997) state that the high velocity of Nova Sco could be obtained by having the pre-SN mass ratio above 0.24, i.e. $M_{\rm He} \leq 9.6$ (they use 2.3 and 4 $M_\odot$ for the current masses). However, this is not in agreement with the assumption in their equation, that the maximal amount of mass is lost. Using our modification (Eq. (1)) to their equation, we find indeed that for their masses it is impossible to obtain a velocity higher than 93 km s $^{-1}$, in agreement with our findings that the post-SN orbit must be different from the current orbit.

The fact that black holes in X-ray binaries may have lost several tens of percents of their progenitor mass in the SN, makes it necessary that some of their progenitor (helium) stars must have had masses above 10 $M_\odot$, which is in clear disagreement with the suggestion from some stellar evolution models that all Wolf-Rayet stars have a mass $\lesssim$ 3.5$M_\odot$ at the moment they explode in a supernova (Woosley et al., 1995).

Finally, it should be noticed that the conclusion that black holes eject a substantial amount of material during their formation has consequences for the orbital period distribution of close black hole pairs, which are expected to be prime sources for ground based gravitational wave detectors. Mass ejection will widen the orbit, which happens twice during the formation of a black hole pair, possibly preventing black holes to form in a close orbit at all. Only kicks from an asymmetry in the SN could then form close pairs. But as shown above, there is not much evidence for kicks and the magnitude of any kicks is severely limited to < 40 km s^{-1} by the black hole X-ray binaries with low mass donors, unless the black holes in these system formed in a direct collapse.

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